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Design of a new full UHV compatible motion system

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Abstract - The ALBA synchrotron light facility is a 3GeV storage ring able to work in top up mode which delivers X-Ray beams to seven beam lines, already in operation. During this first beam lines construction phase all the beam lines has been commissioned and placed in operation successfully. Many of beam line mechanical equipment's' started up during this period includes different UHV motion systems which have demonstrated diverse performances related with the type of solution applied to solve the intrinsic vacuum compatibility problems. The equipment's includes many approaches: from air side by means linear and rotation feeds-through, motor and mechanism encapsulations, etc… All these systems have shown some drawbacks: very short duty cycles, high frictions, heating, the added complexity of the necessity of the feed-through, and even in some punctual case the system simply has fail. In order to deal with all this issues a new motion system design is developed full UHV compatible: all items are vacuum compatible avoiding any encapsulation; all moving elements are rolled resulting frictionless system customized with special materials for the vacuum compatibility which results in turn to maintenance free system. Also the system is designed to support the payload permanently in continuous operation avoiding periodic duty cycles up to in theory infinite life. This for a system which gives 5 mm range for a 250 N maximum payload reaching up a resolution better than 0,1µm. This design has been patented, patent application number U201431338.

***Keywords*:** Ultra-high-vacuum mechanics, UHV motion system, UHV motor.

1. Introduction

Three of the seven first Phase ALBA Beam Lines are equipped with Kirkpatrick-Baez mirrors close to sample position. All these mirrors have four motorization systems for each vertical and horizontal focusing mechanism: a motor for the vertical/horizontal positioning, a motor for the pitch adjustment and two motors of the mirror bender mechanics; all of them are identical.

This motion system are mounted inside the mirror vessel thus must be UHV compatible systems. Precision mechanics inside vacuum requires always complex solution. This current motion system is based on an encapsulated stepper motor with a metric lead screw encapsulated also in a hydro form bellow. This lead screw is friction system, its axial support as well as the spindle axial guide are also friction solutions, which are very compact but at the same time very delicate. The end of the hydro form bellow is a blank cap which includes a ball for punctual contact with the moved, pushed, system. Unfortunately the ball it is not rolling which end to the last friction point in the mechanical chain when inducing an angular movement with this linear motion system.

Moreover the system is in vacuum conditions, and due the friction and motor operation, the system heats up rapidly obligating to work with a duty cycle of 3 minutes of motor switch off after each three minutes of continuous working.

All these makes a very delicate system which ends with the failure of some of these motors with just few days of operation during the commissioning. The system had already shown some symptoms during the metrology where was clearly visible motor step systematic loses and big precision errors and backslash. Next Figure 1. a. show the positioning error of these motors and Figure 1. b. the motion system positioning versus, both, the motor steps. Red lines indicates the motor is moving in positive direction and blues one moving in negative back.

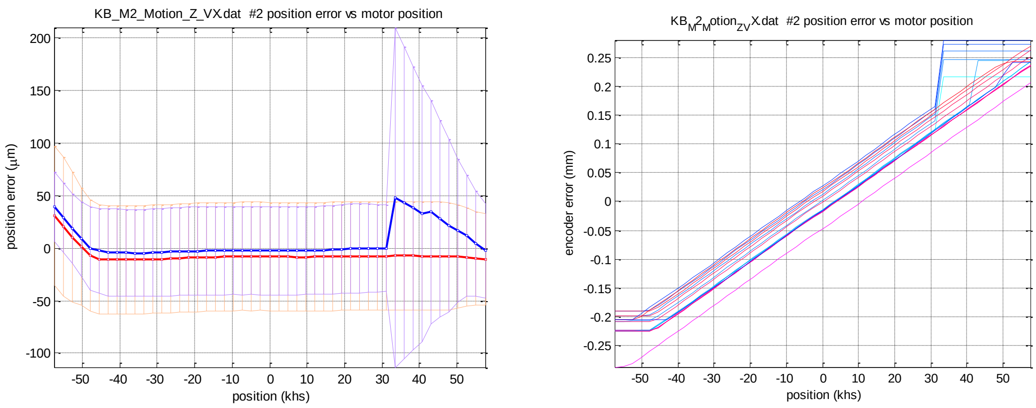


Fig. 1. a. Position error. b. Position

The failure of some of these motors places some of the beam line in an operational commitment situation. In some cases they have simply placed the motors in a fixed configuration with the resulting lack of versatility. The other Beam Line has simply replaced the damaged one by improved motorization being still the same concept and failing again with the time.

In order to solve definitively these UHV motion system issue ALBA has started the design and construction of a new full UHV compatible motion system which avoids all the problems presented above. The solution proposed is completely different conceptual mechanics of the current ones making a system much more robust but still very resolutive.

2. Specifications

In order to avoid all the problems that have shown the encapsulated motorization presented above the system have been specified in very clear guide lines: a full UHV compatible motion system which must achieve:

- 5 mm range (±2,5 mm)
- 250 N Payload
- Irreversible under payload
- Long duty cycles (or continuous movement if possible)
- Full UHV compatible
- No air encapsulations
- 0,1 µm resolution
- Frictionless mechanics
- “miniaturized”
- Long life time, fatigue.

But this new design is not only intending to solve the problems with the ALBA Kirkpatrick-Baez mirror motion system also it is thought to be standards UHV motion system for general purposes, compact and with clear interfaces for many other possible applications.

2. Conceptual solution

In order to deal with all issues in an integrated approach a completely different solution is proposed: an eccentric wheel supported on a shaft. This have all contacts, both shaft ends, as well as the cam on rolled elements. Next Figure 2 shows the basic concept of the motion system.

It consist of a shaft where the central zone has a displaced, non-concentric shaft by 2.5 mm, axis. This shaft is in turn supported on the extremes by bearings. On the motor side this is two “O” configuration angular contacts bearing for on-the-axis shaft holding and the opposite side is a deep grove bearing with the outer ring free for shaft stress and thermal expansions release. The central eccentric shaft is covered also by bearing for rolling contact to the “pushed” target.

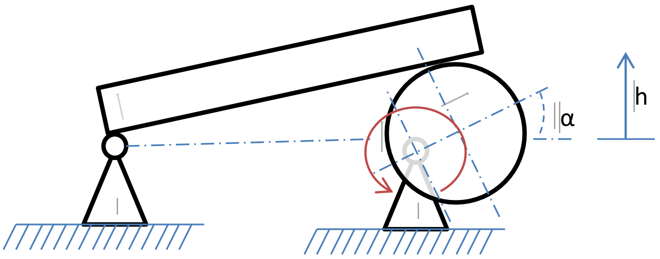


Fig. 2. ALBA UHV Motion System Concept

Next Figure 3 shows a 3D view of the detailed design of the UHV motion system. They are listed the main parts of them bellow.

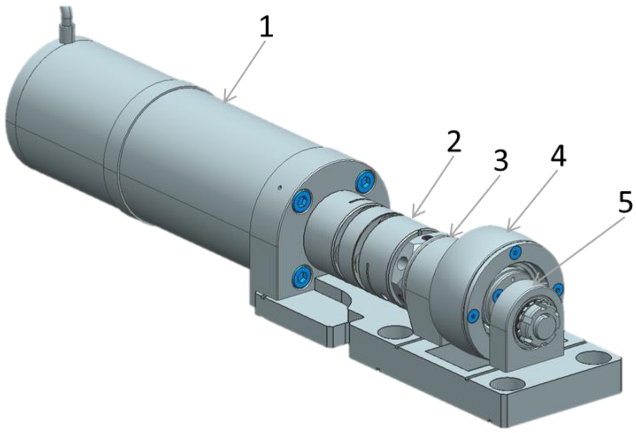


Fig. 3. ALBA UHV Motion System

Main parts:

- Stepper motor plus reducer.
- Flexible coupling
- Shaft support bearings
- Cam
- Shaft end bearing

All parts composing the motion are full Ultra High Vacuum compatible:

- Currently the market already offers full compatible UHV for vacuum levels better than 10^{-10}mbar, Phytron is the main manufacturer of these motors.

- The market also offers full compatible UHV bearing, despite they are not designed for this environment it is possible to find Stainless Steel ring bearing with Si_3N_4 balls and asking PEEK cages as a customized feature. This material combination also avoids the necessity of greasing. As previously shown (Délio Ramos, 2008).
    - It is also possible to do it with full ceramic bearings with Si_3N_4. They are delicate to misalignments but still suitable. Some of the prototypes will be done with full ceramic bearings.
- Coupling: Ruland® offers the possibility to customize in full Stainless Steel material their model for double disk type which are backlash free.
- Nothing is encapsulated.
- All elements could support higher than 100º temperature as has to be bakeable.
- All machined parts are UHV compatible, Stianless steel or bronze.

Next Figure 4 shows a detailed cross section.

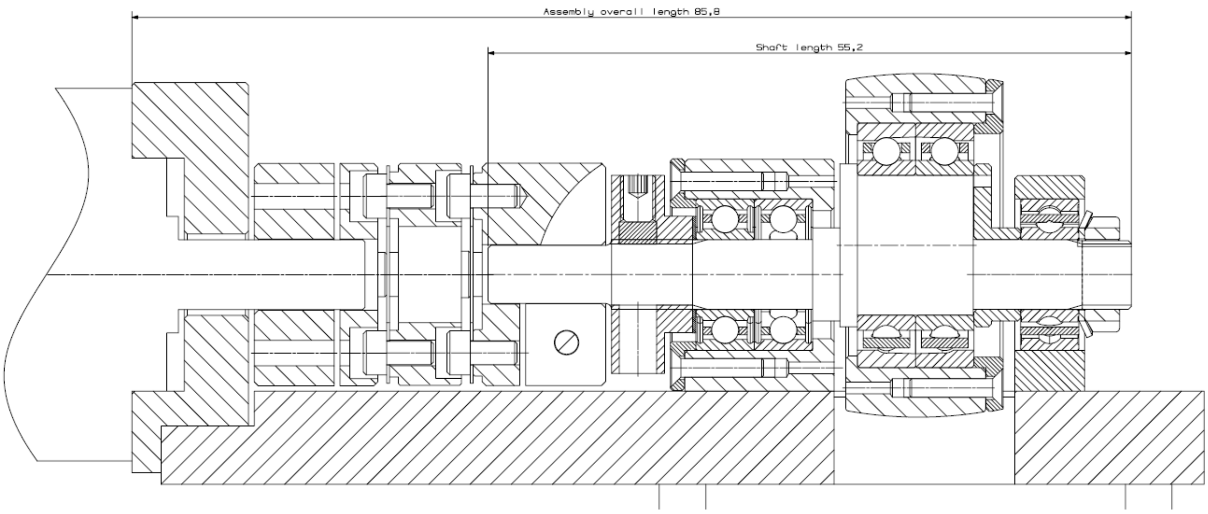


Fig. 4. ALBA UHV Cross section

3. Design validation

In order check the performances of the system some calculation has been done analytically as well as by means FEA tools. The main parameters where to achieve good performances figures are:

- Motor, under maximum payload:
    - Irreversibility
    - Resolution
- Maximum stress
- Fatigue
- Maximum deformation
- Maximum temperature under continuous operation
- Thermo mechanical stress under bake out temperatures

3.1. Motion system

Being an eccentric cam mover the torque that is transmitted to the motor is directly the maximum payload specified by the eccentric distance:

• Pay load: F= 250 N.
• Level arm: eccentric: e=2.5 mm.

With this the torque transmitted to the reducer exit through the shaft is:

$$T = F \cdot e \quad (1)$$

Where:

- T is the torque on the shaft: T=0.625 Nm

3.1.1. Irreversibility

In this case the motor is calculated with the irreversibility as it is a critical characteristic. The UHV motors that the market offers could not have brakes. Moreover the maximum available standard reduction ratio is chosen to deal with this irreversibility which should deal in turn with the resolution requested.

The full motor reference is: SS32.200.2,5-S-VGPL32.3/512-UHVG-4Lp. Next Figure 5 shows the motor characteristic curve.

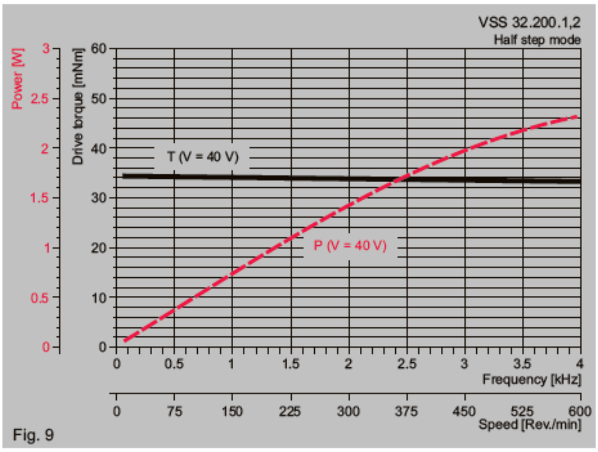


Fig. 5. Caption for figure goes at the bottom

With this the torque on the motor could be calculated:

- Reduction ratio: i=512.
- Detent torque: T_d=3.3e-3 Nm

$$T_m = \frac{T}{i} \quad (2)$$

- Torque on the motor: T_m=1,22e-3 Nm
- Safety margin: S_m=2,458

For this irreversibility calculation the reducer efficiency is not considered as is giving extra safety margin.

In order to mathematically model the system Next Figure 6 represents the conceptual model of the mechanism.

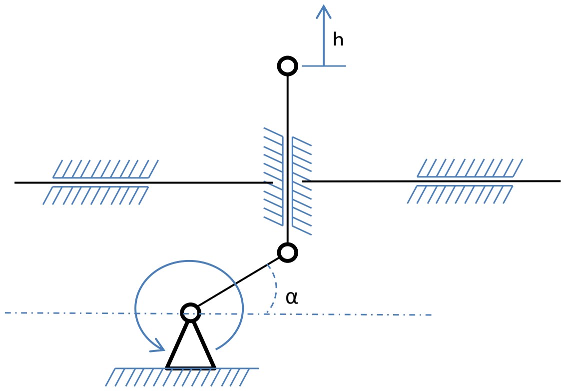


Fig. 6. Mechanism model

Following this model the transmitted movement's equation is like this:

$$h(\alpha) = e \cdot \sin(\alpha) \tag{3}$$

Next Figure 7 shows the motorization movement in function of the cam angle, considering the 0 rad when the line defined by the center of the shaft and the center of the eccentric is horizontal:

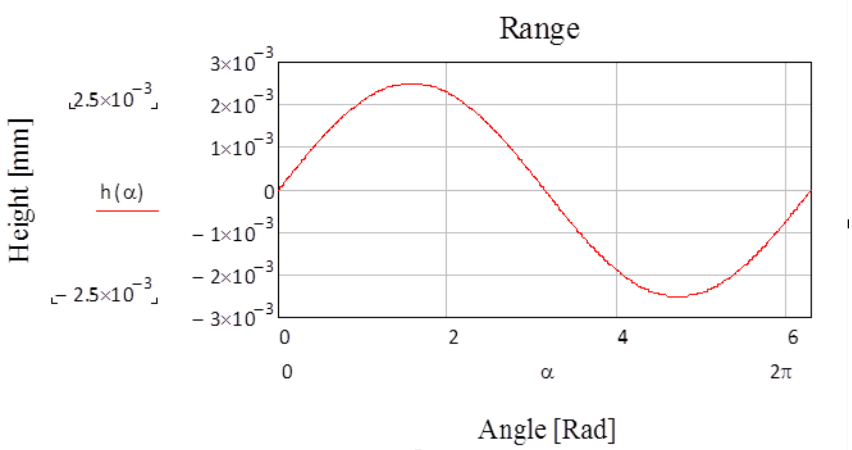


Fig. 7. Range as α function

3.1.2. Resolution

Looking to the previous graph the resolution is just the vertical axis variation respect Δα, this is simply the derivative:

$$r_c = \frac{\delta h(\alpha)}{\delta \alpha} \tag{3}$$

The main drawback of the system is the resolution variation. When the eccentric is vertical, π/2, the resolution tends to infinite and the lower resolution is at the eccentric at horizontal position. The previous equation 3 is the continuous resolution but taking into account the system have a stepper motors the resolution at each angular position is defined by:

$$r(\alpha) = \int_{\alpha-\Delta\alpha}^{\alpha} r_c(\alpha)d\alpha \tag{4}$$

Where:

- Δα is the full step angular resolution (displacement)

$$\Delta\alpha = 2\pi\frac{1}{p}\frac{1}{i} \tag{5}$$

- P is the stepper motor full steps: 200.
- And i is the reducer reduction ratio, i=512.

Next Figure 8 graph shows the resolution in function of the eccentric angle α:

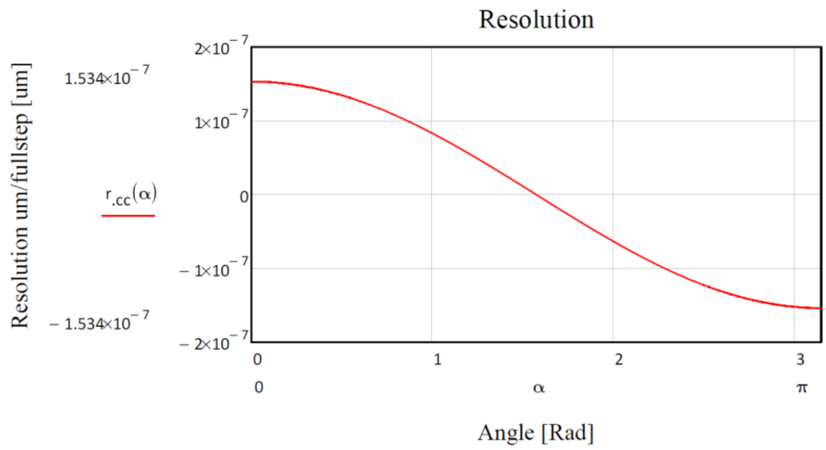


Fig. 8. System resolution

Thus the resolutions at the range extremes and in the middle are, respectively:

- $r(0) = 0.153\ \mu m$
- $r(\pi/2) = 4.706 \cdot 10^{-6}\ \mu m$
- $r(\pi/4) = 0.108\ \mu m$

This is full step resolution and it is higher than specified, but stepper motors have the stable positions at half step. Then the final resolution is:

- $r(0) = 0.0765\ \mu m$

Moreover the motor supplier offers nonstandard reductions, but these are almost twice the price and with reducer of four stages instead of 3, this means longer set up thus less compactness. The customized reduction would be a maximum of 1600 ratio, this would mean in the worst case resolution angular position:

- $r(0) = 0.05\,\mu m\ at\ full\ step$ (with customized reduction ratio, i=1600)

3.2. Maximum stress

In order to check the stress under the maximum payload has been calculated, analytically the flexion of the shaft, as well as using FEA tools of the whole model. In this paper the numerical calculations are shown as are the more accurate ones.

Next Figure 9 shows: a. the boundary conditions and b. the maximum stress of the system. As expected this is located on the shaft.

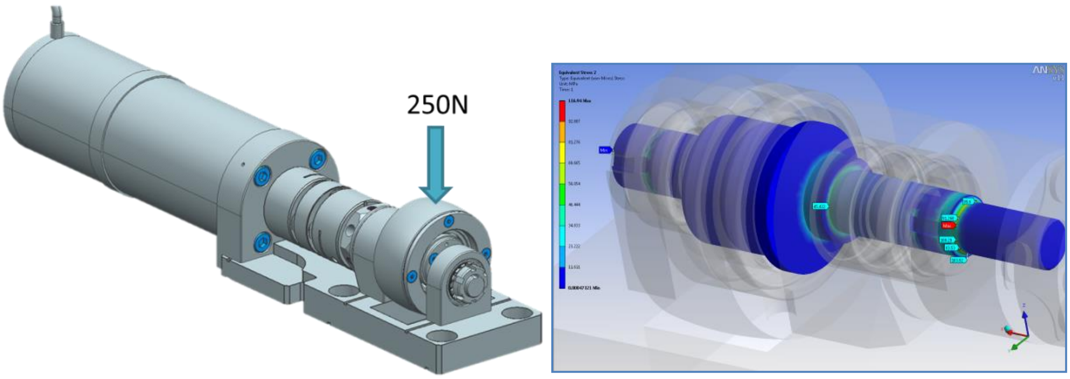


Fig. 9. a. Boundary condition. b. Maximum stress

The maximum stress is 117 MPa. All machined parts materials must be also UHV compatible so all parts are done in Stainless Steel less one. In order to ensure infinite lifetime under fatigue conditions a special Stainless Steel is chosen. Almost all machined parts, which are the structural supporting ones, are done with the same material to avoid differential thermal expansions which could end with high stresses during bake out.

The material chosen is a modified AISI-420 but pretreated with full material performances without post machining treatments. This avoids fine remachining after hardening. This material has a very high elastic limit and still maintaining the good fatigue performances despite the pre-hardening. Next Table 1 shows the main mechanical properties of this material.

Table. 1. Modified AISI-420 Mechanical characteristics

Characteristic	**20º**	**200º**
Elastic limit [MPa]	1150	1060
Elastic Limit, R_p0,2 [MPa]	1020	930
Fatigue Limit[1] [MPa]	600	-

[1] Rotating bending fatigue limit

Next Figure 10 shows the FEA calculations with the showing that more than 10^6 cycles without damage is achievable.

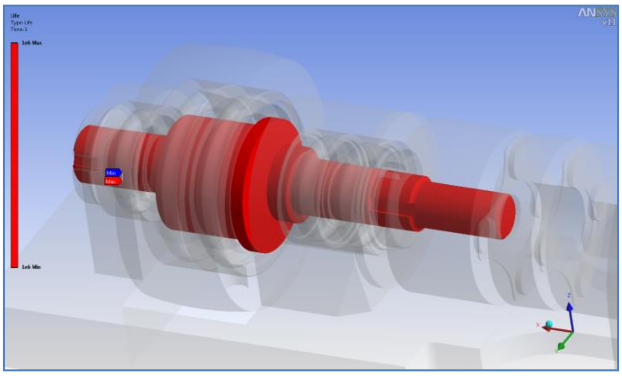


Fig. 10. Fatigue life cycles calculation

With this FEA also the total deformation is shown. The shaft has been checked despite the good previous results just for to ensure the total bending displacement is not too high. Next Figure 11 shows the result which is about 0,02 mm.

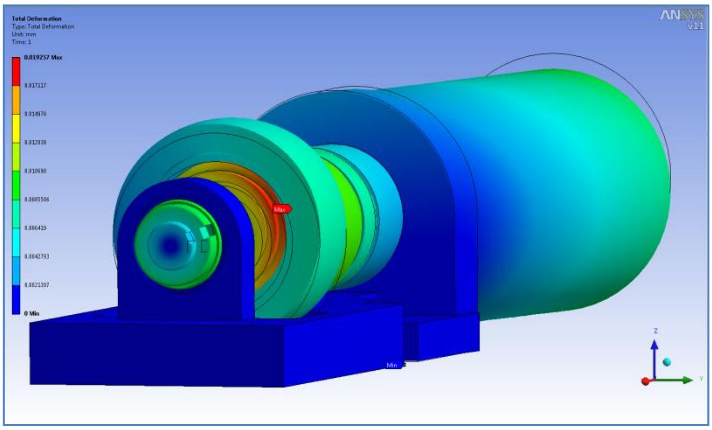


Fig. 11. Maximum deformation

3.3. Motor heating

The motor under continuous operation will heat itself and the mechanics around. And this is worsening by the vacuum environment which isolates and does not allow dissipating the heat fluently. Looking to the motor characteristic curve the maximum power delivered by the motor is about 2,3W. Previous Figure 5 shows this motor curve. A total power of 2,5W has been considered applied to the motor as boundary condition to calculate the steady state of the motor and its thermo mechanical stresses and deformations, by means the FEA tools.

A basic 3D model of the surrounding elements has been introduced in the model to simulate the conduction elements which will help to the power dissipation. Next Figure 12 shows the model and the result.

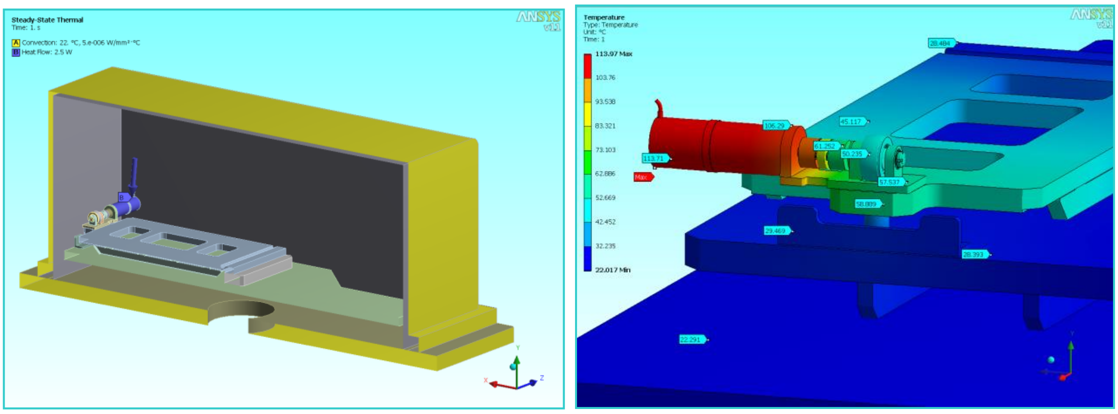
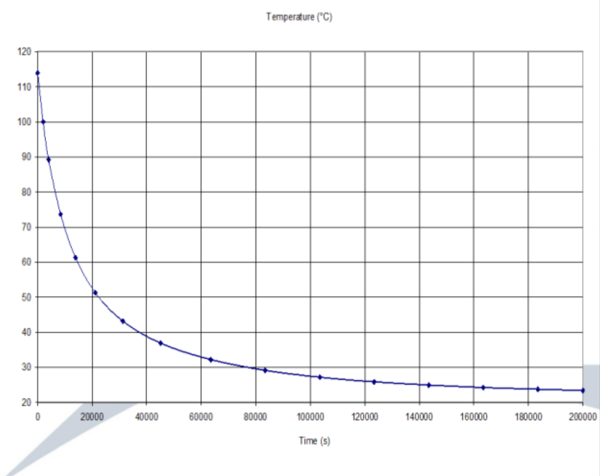


Fig. 12. Motor Heating

The maximum temperature at steady state is 114º which is perfectly assumable by the mechanics. Moreover the time to reach it up is quite long as shown in next graph of Figure 13. It is needed about 28 h of continuous operation to reach this steady state. By the time needed to move and focus the mirrors about several minutes this means that continuous operation is possible. Moreover copper braid heat conductors can mounted as the mirror vessels has a water cooling circuit.



Time (s)	Temperature (°C)
0	113.97
2000	100.0479
4000	89.24922
8393.979	73.69079
13878.86	61.29814
21126.26	51.29403
31175.74	43.21326
45015.25	36.91716
63432.77	32.21747
83432.77	29.16756
103432.8	27.20753
123432.8	25.87797
143432.8	24.93834
163432.8	24.25338
183432.8	23.74249
200000	23.40815

Fig. 13. Motor Heating steady state time

The maximum stress under this condition is about 34 MPa on the shaft and is shown in the next Figure 14.

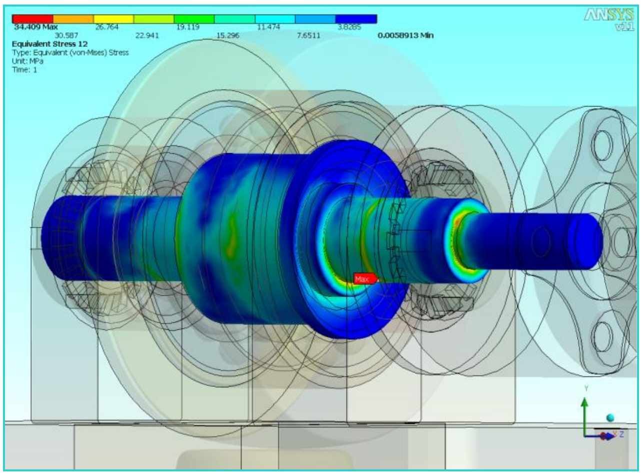


Fig. 14. Motor Heating thermo-mechanical stress

3.4. Bake out

As being optical equipment placed in hard as well soft X-Ray Beam Lines the bake outs are mandatory. Then the possible damages during this process have to be eliminated considering them during the design. The current ALBA equipment's are bake at 80º but as being proposed to be also a standard UHV motion system, it is checked at 150º. Next Figure 15 shows the totals stress induced by the differential thermal stresses of the bake out.

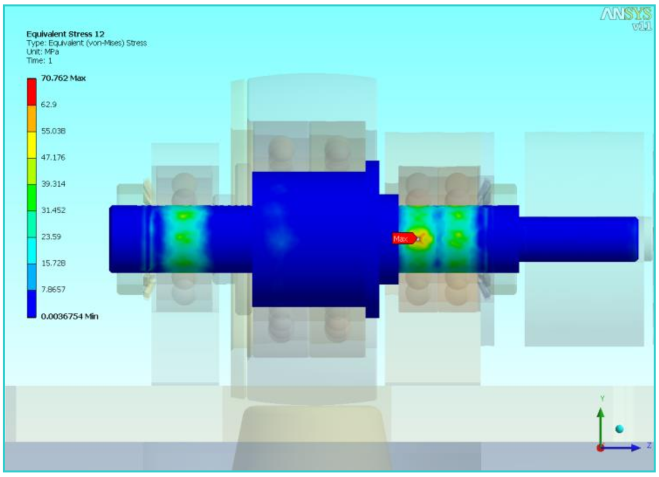


Fig. 15. Bake out thermo-mechanical stress

This is about 71 MPa which is perfectly assumable.

4. Tests

With the objective to perform as close as possible the working conditions tests a test bench set up has been design and constructed able to be placed under a vacuum chamber. Next Figure 16 shows the set up.

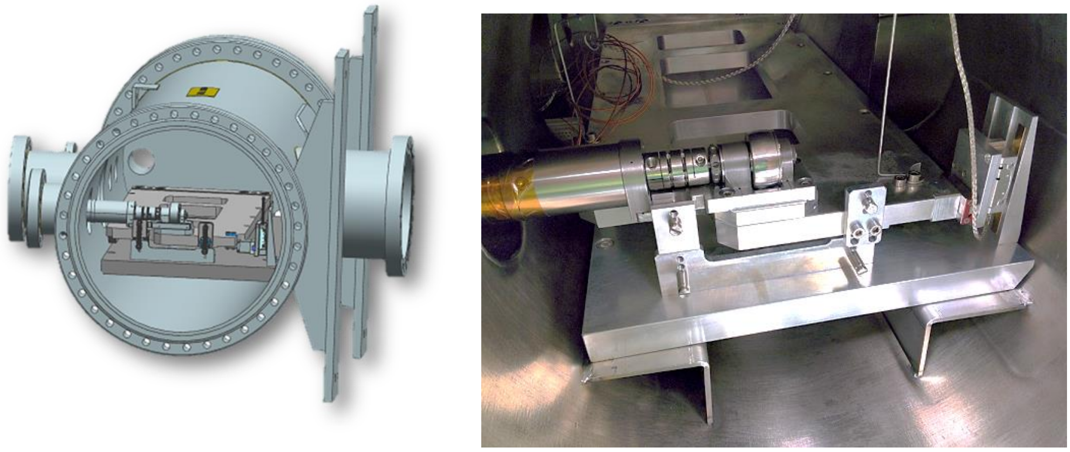


Fig. 16. Test bench

The test bench includes an optical encoder with about 1 nm resolution interpolator full UHV compatible and bakeable. The encoder is shown in the last Figure 16 at the right. This is the only way to test the motion under vacuum as laser interferometer could not be implemented in-vacuum.

On the platform a total weight of 25kg has been placed to introduce the 250N payload. The motor have been moved to the horizontal position and the motor have been switched off to check the irreversibility. The encoder has not shown a minimum drift with this test.

The most significant tests to check the performances of the motion are the precision and resolution tests. These are done on air to calibrate the encoder by means a laser interferometer Renishaw® ML-10 Gold Edition as well as preliminary reference test for later comparison after bake out. In order to check the full UHV compatibility a RGA has been done after the bake out. So the main tests are:

- Motion precision, resolution on air. With interferometer.
- RGA after bake out
- Motion precision, resolution under vacuum after bake out with encoder.

The first test on air with the interferometer is the accuracy of the motion. The accuracy of the motion is about ±2,42µm in the full range with repeatability of 55 µm. Nest Figure 17 shows this accuracy error. This is a very smooth movement which means the fine functioning of the motion.

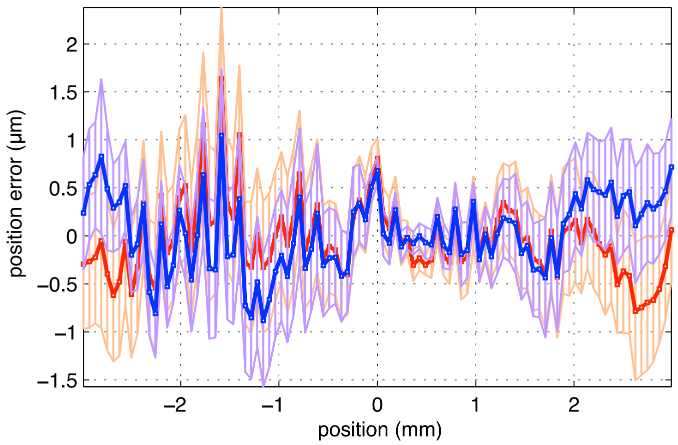


Fig. 17. Motor accuracy, on air.

The resolution is tested with motor half steps. Next Figure 18 shows the graph where is possible to see reasonable good uniformity of the steps demonstrating the good resolution performance up to 0.076µm for half step.

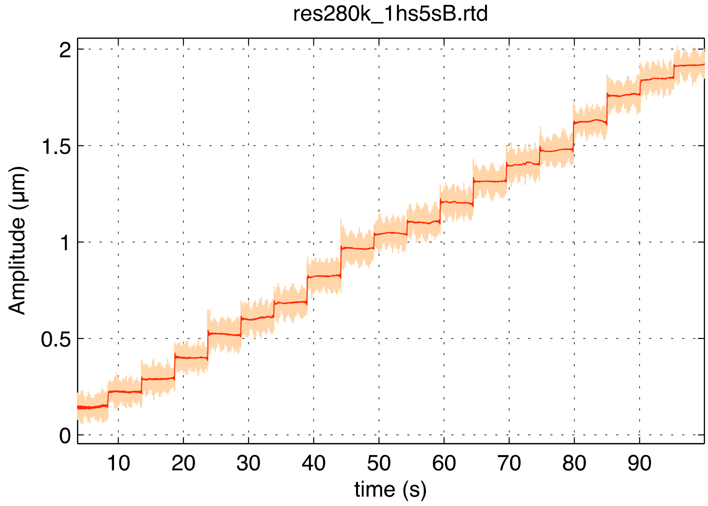


Fig. 18. Motor resolution, on air

After the air tests the chamber has been pumped down and a bake out has been done. Unfortunately at the moment of the test some of the old the motions system were failing so the new one, the two first prototypes, are to be installed thus cannot be tested up to the limit. For this reason the bake out has been done at 80º. The vacuum after a three days bake out is about $2 \cdot 10^{-8}$mabar. Taken into account the short bake out the RGA scan shows relatively low peaks in all species a part of water and oxygen demonstrating the vacuum compatibility of the all the parts, specially customized ones, like hybrid bearing, coupling and the stepper motor.

After the bake out some of the test were repeated. This test under vacuum shows that there is no degradation of the system, the accuracy and the resolution are maintained or even slightly better. Next Figure 19 shows the accuracy graph which can be compared with Figure 18. During the test the temperature of the motor is directly related to the speed and the idle current of the motor. Full power speed at maximum allowable current with 100% of idle current rises up the temperature at 90º within 10 minutes.

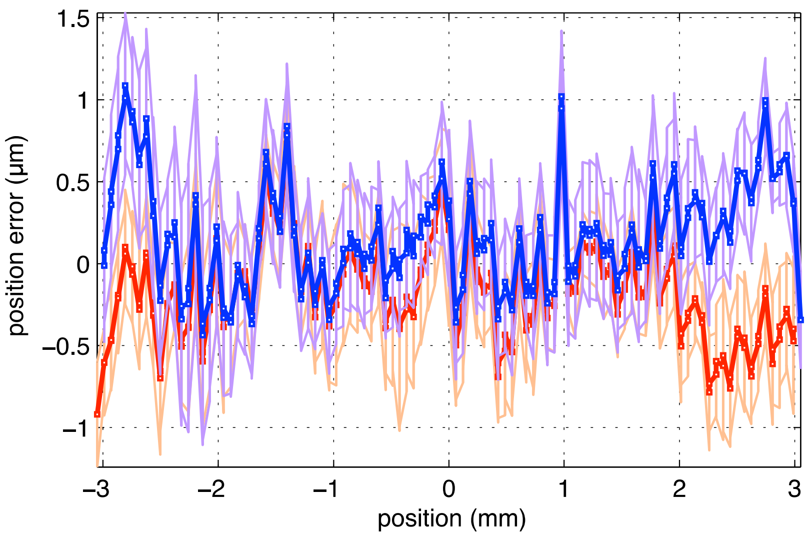


Fig. 19. Motor accuracy under vacuum, after bake out

Next Table 2 summarizes the figures of the mechanical tests under vacuum after the bake out:

Table. 2. Final motion performances summary, under vacuum, after bake out

Characteristic	Figure
Average Resolution	61.03 nm
Repeatability	0,37 µm
Accuracy	1,78 µm

4. Conclusion

The construction of a full compatible and reliable UHV motion system is possible with 250 N of payload and 5 mm of range, frictionless and without any encapsulation. Next table 2 shows the summary of the performances.

Table. 3. Motion system performances summary

Parameter	Performance	Specified
Range	+/- 2,5 mm	+/- 2,5 mm
Resolution	< 0,153 µm 0,765 µm at Half step	< 0,1 µm
Accuracy	±2,42µm	-
Repeatability	< 1 µm	-
Payload	250 N	250 N
Lifetime	>10^6 Cycles	Infinite
Range elapsed time	13 s	< 1 min
Vacuum	All Standard & materials UHV compatible	UHV compatible 10^{-10}mbar
Bake out	Tested at 80º Theory at150º	80º
Mechanics	Frictionless	Frictionless
Maintenance	Ceramic balls, maintenance free motor	Maintenance free

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